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14. ABSTRACT
Fluid-structure interaction (FSI) is known to be one of the most challenging classes of problems in scientific computing. With creative methods for coupling the fluid and structure, we can increase the scope and efficiency of the FSI modeling. Multiscale methods, which now play an important role in computational mathematics, can also increase the accuracy and efficiency of the computer modeling techniques. The main objective of this project is to develop new multiscale methods specifically targeting FSI computations. Some of these methods are multiscale in

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Multiscale and Sequential Coupling Techniques for Fluid-Structure Interaction Computations

ABSTRACT

Fluid-structure interaction (FSI) is known to be one of the most challenging classes of problems in scientific computing. With creative methods for coupling the fluid and structure, we can increase the scope and efficiency of the FSI modeling. Multiscale methods, which now play an important role in computational mathematics, can also increase the accuracy and efficiency of the computer modeling techniques. The main objective of this project is to develop new multiscale methods specifically targeting FSI computations. Some of these methods are multiscale in the way the time-integration technique is performed (i.e. temporally multiscale), some are multiscale in the way the spatial discretization is done (i.e. spatially multiscale), and some are in the context of the sequential-coupling techniques that we are developing in this project. The objectives of the project include determining the range of applicability of these multiscale and sequential-coupling techniques and generating an engineer's guide to multiscale FSI computations.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/10/04 1(9	Kenji Takizawa, Nikolay Kostov, Anthony Puntel, Bradley Henicke, Tayfun E. Tezduyar. Space–time computational analysis of bio-inspired flapping-wing aerodynamics of a micro aerial vehicle, Computational Mechanics, (08 2012): 0. doi: 10.1007/s00466-012-0758-y
2012/10/04 1(8	Kenji Takizawa, Bradley Henicke, Anthony Puntel, Nikolay Kostov, Tayfun E. Tezduyar. Space–time techniques for computational aerodynamics modeling of flapping wings of an actual locust, Computational Mechanics, (08 2012): 0. doi: 10.1007/s00466-012-0759-x
2012/10/04 1(7	YURI BAZILEVS, MING-CHEN HSU, KENJI TAKIZAWA, TAYFUN E. TEZDUYAR. ALE-VMS AND ST-VMS METHODS FOR COMPUTER MODELING OF WIND-TURBINE ROTOR AERODYNAMICS AND FLUID–STRUCTURE INTERACTION, Mathematical Models and Methods in Applied Sciences, (08 2012): 0. doi: 10.1142/S0218202512300025
2012/10/04 1(6	KENJI TAKIZAWA, TAYFUN E. TEZDUYAR. SPACE–TIME FLUID–STRUCTURE INTERACTION METHODS, Mathematical Models and Methods in Applied Sciences, (08 2012): 0. doi: 10.1142/S0218202512300013

TOTAL: 4

Number of Papers published in peer-reviewed journals:

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Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
2012/10/04 1'	12	Tayfun Tezduyar, Kenji Takizawa. Space–Time Computational Fluid–Structure Interaction Techniques, 19th National Computational Fluid Dynamics Conference, Penghu, Taiwan, 2012. 2012/08/16 01:00:00, . : ,
2012/10/04 1'	11	Kenji Takizawa, Bradley Henicke, Anthony Puntel, Nikolay Kostov, Tayfun Tezduyar. Space--Time Computational Techniques for the Aerodynamics of Flapping Locust Wings}, International Workshop on Future of CFD and Aerospace Sciences. 2012/04/23 01:00:00, . : ,
2011/08/15 1ł	5	Kenji Takizawa, Tayfun E. Tezduyar. MULTISCALE SPACE--TIME COMPUTATION TECHNIQUES, Computational Methods for Coupled Problems in Science and Engineering. 2011/06/20 01:00:00, . : ,

TOTAL: 3

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2012/10/04 1'	10	Kenji Takizawa, Darren Montes, Spenser McIntyre, Tayfun Tezduyar. Space--Time VMS Methods for Modeling of Incompressible Flows at High Reynolds Numbers, Mathematical Models and Methods in Applied Sciences (06 2012)
2011/08/15 1ł	4	Kenji Takizawa, Bradley Henicke, Anthony Puntel, Timothy Spielman, Tayfun E. Tezduyar. Space--time computational techniques for the aerodynamics of flapping wings, Journal of Applied Mechanics (08 2011)
2011/08/15 1ł	3	Kenji Takizawa, Bradley Henicke, Darren Montes, Ming-Chen Hsu, Yuri Bazilevs. Numerical-Performance Studies for the Stabilized Space-Time Computation of Wind-Turbine Rotor Aerodynamics, Computational Mechanics (05 2011)
2011/08/15 1ł	2	Kenji Takizawa, Bradley Henicke, Ming-Chen Hsu, Yuri Bazilevs. Stabilized Space--Time Computation of Wind-Turbine Rotor Aerodynamics, Computational Mechanics (03 2011)
2011/08/15 1ł	1	Kenji Takizawa, Tayfun E. Tezduyar. Multiscale Space-Time Fluid--Structure Interaction Techniques, Computational Mechanics (01 2011)

TOTAL: 5

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Anthony Puntel	0.00	
Nikolay Kostov	0.23	
Matthew Fritze	0.13	
FTE Equivalent:	**0.36**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Tayfun Tezduyar	0.13	
FTE Equivalent:	**0.13**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Anthony Puntel

Total Number: **1**

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Abstract

Fluid-structure interaction (FSI) is known to be one of the most challenging classes of problems in scientific computing. With creative methods for coupling the fluid and structure, we can increase the scope and efficiency of the FSI modeling. Multiscale methods, which now play an important role in computational mathematics, can also increase the accuracy and efficiency of the computer modeling techniques. The main objective of this project is to develop new multiscale methods specifically targeting FSI computations. Some of these methods are multiscale in the way the time-integration technique is performed (i.e. temporally multiscale), some are multiscale in the way the spatial discretization is done (i.e. spatially multiscale), and some are in the context of the sequential-coupling techniques that we are developing in this project. The objectives of the project include determining the range of applicability of these multiscale and sequential-coupling techniques and generating an engineer's guide to multiscale FSI computations.

Objective

Fluid-structure interaction (FSI) continues to be one of the most challenging classes of problems in scientific computing. Creative methods for coupling the fluid and structure parts are essential in increasing the scope and efficiency of FSI modeling. Multiscale methods will also continue to play an important role in computational mathematics and will increase the accuracy and efficiency of the computer modeling techniques. In multiscale computations, time-step size restrictions, imposed by numerical stability and accuracy considerations, pose a challenge. These restrictions depend on grid refinement, and also fluid and structure might have different time-step size requirements. Reducing the time-step size (or increasing the time-integration power) everywhere is the easiest way but not computationally efficient. Our objective is to develop new multiscale methods specifically targeting FSI computations. Some of these methods are multiscale in selecting the time-integration and time-step size (i.e. temporally multiscale), some are multiscale in selecting the grid refinement and interpolation power of the functions used (i.e. spatially multiscale), and some are in the context of the sequential-coupling techniques that we are developing in this project. Our objective includes determining the range of applicability of these multiscale and sequential-coupling techniques and generating an engineer's guide to multiscale FSI computations.

Approach

In the sequentially-coupled FSI approach, we first have a fully-coupled FSI computation with baseline spatial and temporal accuracy. The baseline grid refinement level, interpolation power of the finite element functions used, time-step size and the time-integration power determines that accuracy. Using the baseline structural deformation as given, we improve the spatial and temporal accuracy of the fluid mechanics part by carrying out fluid-only computations with better grid refinement, more interpolation power for the finite element functions, smaller time-step size and more time-integration power. In this way, we can, for example, compute the unsteady wake flow more accurately. Similarly, by using the baseline fluid mechanics forces at the fluid-structure interface as given, we can improve the spatial and temporal accuracy of the structural mechanics part by carrying out structure-only computations. In this way, we can, for example, compute the stress concentration at a given point more accurately. Although it will be more challenging, we also plan to use these multiscale spatial and temporal accuracy enhancements in the context of fully-coupled FSI computations. One of the ways to do that, for example, is to use, in the context of a fully-coupled FSI computation, more time-integration power in the fluid part or in certain zones of the fluid part. Increasing the time-integration power will increase the range of time-step sizes that can be used while maintaining the stability and accuracy of the computations.

Scientific Barriers

Data exchange in multiscale computations will be one of the main challenges, especially in the context of a fully-coupled FSI computation. Projecting solutions between grids with different refinement levels, especially from a coarse grid to a fine grid, is always challenging, and the way we address that challenge will quite often be problem-specific. Coupling between zones with different time-step sizes or different time-integration powers is another challenge that needs to be addressed. Sequentially-coupled FSI computing is rather intensive in I/O access and that needs be addressed in a parallel computing environment.

Significance

Accurate and robust FSI modeling is key to a realistic simulation that takes into account the true nature of a challenging problem in computational science and engineering. Multiscale techniques, in general, give us more accuracy and efficiency. The sequential-coupling techniques, which will be limited to certain classes of FSI problems, gives us more computational efficiency and more flexibility. With that flexibility and a multiscale approach, we can increase the spatial and temporal accuracy of the results in an efficient way. Multiscale and sequential-coupling FSI computer modeling techniques that can increase the accuracy and efficiency of the computations in a parallel-computing setting will help computational scientists and engineers bring solutions to complex, real-world problems, including those relevant to the US Army and the Department of Defense. We expect that the type of problems that will benefit from such powerful and practical FSI modeling techniques will include the flapping wing aerodynamics of Micro Air Vehicles (MAV), aerodynamics of Unmanned Air Vehicles (UAV), Micro-Electro-Mechanical Systems (MEMS), aerodynamics of parachutes, and inflatable structures subjected to wind loads.

Accomplishments

Space-Time Turbulence model

A turbulence model has been developed in conjunction with our space-time finite element method, namely the DSD/SST method. This is the space-time version of the residual-based variational multiscale (VMS) method. We call this new technique DSD/SST-VMST (i.e. the version with the variational multiscale turbulence model). We call the original version DSD/SST-SUPS (i.e. the version with the SUPG and PSPG stabilization). We also derived an alternative form of DSD/SST-VMST, which has the advection term in the non-conservative form. The set of DSD/SST-VMST technique we developed include using different stabilization parameters for the "LSIC" term (i.e. the stabilization based on least-squares on incompressibility constraint). The method belongs to the class of the large eddy simulation (LES) methods. LES methods require some minimum resolution. The required resolution is usually high near the boundary layer. We introduced various alternative versions of the formulation, in terms of how the LSIC term is defined and also in terms of how the advective term is treated. The evaluation of these alternative versions requires patience and diversity in the problems computed.

Test computation with a rigid airfoil and unsteady flow field

We designed this special test problem, and generated a special mesh, for first evaluating the accuracy of the DSD/SST-VMST method and comparing it to DSD/SST-SUPS formulation. This required writing a special mesh generation program. We used a 64-618 airfoil, with a core rectangular mesh region. We tested both linear finite elements in space and quadratic B-splines in space. We compared the results to experimental data. We showed that VMST performs better, but SUPS, our standard formulation, is also performing at a reasonable level. The details can be found in [1].

Test computation with an airfoil attached to a torsion spring and unsteady flow field

We used the same airfoil and mesh to test how the DSD/SST-VMST and DSD/SST-SUPS techniques perform in a simple FSI problem. The airfoil is attached to a torsion spring. More details on the problem set up can be found in [1]. The core rectangular mesh rotates with the airfoil to maintain a constant mesh resolution near the airfoil. The computations show that the DSD/SST-VMST method gives more accurate results (with less damping) compared to the DSD/SST-SUPS method. More details can be found in [1].

Time approximation with NURBS

We developed a method to approximate motions with temporal NURBS basis functions. This method is a core technique to be used with the techniques highlighted below.

A. Surface motion and deformation representation with NURBS in time

We are now using NURBS basis functions in time to represent the motion and deformation of surfces. This gives us a more accurate, smoother, and more efficient representation in time. To make the pressure continuous in time, position vectors of the surfaces need to be represented with cubic NURBS functions in time, so that their second derivatives in time (i.e. the acceleration), which balances the pressure in the momentum equation, are continuous in time. That is what we implemented.

B. Mesh representation with cubic NURBS in time

Time dependent mesh is represented with temporal NURBS basis function. This allows us to do mesh computations (by solving the equations governing the mesh motion) with longer time in between. This has been successfully tested on 3D computation of the aerodynamics of flapping wings. We need to have the temporal order of NURBS basis functions used in mesh motion match the temporal order used in the surface motion representation. For that reason, for the mesh motion we implemented also cubic NURBS functions in time.

C. Remeshing technique with the mesh representation described above

We proposed the following remeshing technique. Prior to remeshing we perform multiple knot insertions at the instant in time where we want to remesh. Then the basis set will be interpolatory there. With that, the basis functions on two sides of that point in time are separate, i.e. that point is a patch boundary. This has been successfully tested on 3D computation of the aerodynamics of flapping wings. This also has been implemented for cubic NURBS functions in time.

Collaborations and Leveraged Funding

The FSI simulations we carried out for our NASA parachute project helped us to better understand the numerical challenges involved in fluid-structure coupling and multiscale computations. We collaborated with Dr. Yuri Bazilevs from University of California, San Diego, who is an expert in NURBS-based spatial interpolation. We also learned from our NSF project, which was on aerodynamic modeling of the flapping locust wings and which gave us a test platform for our multiscale space-time techniques.

Conclusions

Fluid-structure interaction (FSI) modeling is now an important part of computational engineering and science, with a wide class of applications, including those very relevant to the Army and Department of Defense. We have formulated effective multiscale and sequential coupling techniques for FSI computations that, for certain classes of problems, will increase the efficiency

without compromising the accuracy.
If we cannot resolve the separation point correctly, the stress, which the structure sees, cannot be represented correctly. Higher Reynolds numbers with curved geometry is a difficult case to resolve the separation point for. It is a candidate for the failure cases of the sequentially-coupled FSI technique. Also, accurate temporal representation of the moving and deformation surfaces is important for the overall accuracy of the computations, and for that we use higher-order NURBS functions in time.
A. We concluded that we can compute the aerodynamic forces acting on curved geometries with reasonable accuracy even with relatively coarse meshes if we use a good turbulent model (DSD/SST-VMST), which we developed and described above. The mesh is relatively coarse, however a good boundary layer mesh is required depending on the Reynolds number. We tested different versions of the "LSIC" stabilization, which makes a difference in the solution. We observed that the way advection terms are treated makes a difference, and we are still testing different versions based on that, something that takes significant effort, patience, and a systematic way of looking at the different combinations that can be used.
B. Clearly we need sufficiently higher order functions in time for accurate and smooth representation of the moving and deforming surfaces, at least cubic functions. This is important to keep the fluid pressure continuous and avoid jumps in the forces acting on moving surfaces.
C. Using higher-order NURBS functions in time in representing the mesh motion and in dealing with remeshing also provided robustness and efficiency to our mesh update methods.

Technology Transfer
The computational technology of using NURBS in time approximation, particularly the special techniques described in Items B and C, can be directly used in Army applications requiring aerodynamics or hydrodynamics computations with moving objects. While we tested and demonstrated these techniques in the context of a space-time finite element formulation, they can also be used in different moving-grid contexts, such as ALE finite element or finite volume computations, which are probably more commonly used techniques by the Army research community.

[1] K. Takizawa and T.E. Tezduyar, "Space-Time Fluid-Structure Interaction Methods", Mathematical Models and Methods in Applied Sciences, 22, 1230001 (2012).

Technology Transfer